

ELECTRICAL RESISTIVITY MEASUREMENTS OF INTACT AND FRACTURED GEOHERMAL RESERVOIR ROCKS

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ABSTRACT

Laboratory measurements of the electrical resistivity of intact and fractured representative geothermal reservoir rocks were performed to investigate the resistivity contrast caused by active boiling. Measurements were performed to simulate reservoir conditions with confining pressures up to 100 bars and temperatures to 181°C. Measurements presented are a first step toward making the search for fractures using electrical methods quantitative. Intact samples showed a gradual resistivity increase when pore pressure was decreased below the phase-boundary pressure of free water. When fluid-filled, the prepared fractured samples were 25-50% less resistive than the intact samples and showed larger increases in resistivity when boiling commenced. The resistivity ratio between boiling samples and liquid-saturated samples ranged between 2 and 5. Both intact and fractured samples demonstrated vapor pressure lowering. Analysis of a field test provided the opportunity to evaluate fracture detection using electrical methods at a large scale. Interpretation of electrical resistance tomography (ERT) images using resistivity contrasts determined by laboratory experiments indicates that actively boiling fractures can be identified. These results will lead to improved geophysical diagnostics for locating fractures and regions of active boiling in geothermal reservoirs.

INTRODUCTION AND BACKGROUND

The electrical properties of geothermal rocks are important for numerous reasons including understanding field wide properties, such as defining the field boundaries, following the effects of production including formation of a steam cap, and

tracking injectate. Electrical methods provide the best means to detect and follow fluid movement in the subsurface. These data are of fundamental value for interpreting logs of electrical properties measured in the field. Detection of occult steam, either by electrical or other means, is also important because of the consequences for interpretation of well-interference tests. These tests are a primary tool for evaluating the mass in place in a fluid-dominated geothermal field (Murray et al., 1995). Unknown or occult steam would greatly increase the actual compressibility of the field, introducing errors on mass estimates made under the assumption of a single incompressible (liquid) phase.

Rock electrical properties are sensitive to factors such as the nature and amount of pore saturant, temperature, and pressure (Llera et al., 1990), surface conduction, and microstructural properties such as porosity of the rock matrix. The amount of the pore saturant and its nature (i.e., whether it is liquid water, other fluids, steam, and other gases) and microstructural properties are the most significant factors. Most dry rocks are excellent insulators in vacuo, but saturation with distilled water decreases resistivity by 8 orders of magnitude and more (Duba et al., 1978). In water-saturated rocks, increasing temperature from 25 to 250°C decreases the electrical resistivity by about an order of magnitude (Llera et al., 1990).

Previous electrical measurements on intact samples from The Geysers (Roberts et al., 2001) and Awibengkok (Roberts et al., 2000), indicate boiling phenomena attributed to vapor-pressure lowering. As the properties of fractures play a large role in the performance of geothermal reservoirs, we decided to

investigate samples with prepared artificial fractures in order to assess the electrical signatures which would be indicative of fluid- and steam-filled fractures in situ. Geophysical electrical methods rely on contrast in resistivity to locate fractures and to determine if steam is present. These methods include the long-spacing induction tool, cross-well EM and electrical resistance tomography (ERT).

EXPERIMENTAL PROCEDURE

Experimental Apparatus

A complete description of the experimental apparatus and measuring procedures is reported by Roberts et al. (2001). The apparatus consists of an externally heated pressure vessel with separate pumps and controls for confining pressure and pore pressure on either side of the sample (Figure. 1). Pore pressure was controlled independently between 0 and 5.0 MPa, and for convenience the two systems are referred to as up- and down-stream pressure systems. An impedance bridge was used to measure the resistance of the electrically isolated samples at 1 kHz. Electrical resistivity was calculated from the resistance and geometry of the core. Temperature was measured with type T thermocouples with an

accuracy of $\pm 2^\circ\text{C}$. Resistivity measurements have been made at temperatures up to 275°C . Data collection was automated by use of a scanning unit and microcomputer.

Samples and Preparation

A brief description of the samples studied and microstructural details is listed in Table 1. The first samples selected for electrical properties measurements of fractured rocks were cored from segments of the Awibengkok 1-2 core, taken adjacent to previous samples whose intact electrical properties were studied (Roberts et al., 1999). The porphyritic andesite from 1384 m (4506 ft) is a “typical” flow rock from the reservoir (Hulen and Anderson, 1998). It is dense, medium dark gray-green, with “intense propylitic alteration” as described by Hulen and Nielson (1995) in drill logs from the site. The permeability of nearby core plugs was measured to be $19 \mu\text{Darcy}$ (unpublished data, Unocal Geothermal Operations, Santa Rosa, CA). The porosity of the samples used in the electrical resistivity apparatus was $\sim 3\%$. The breccia selected for study had a much higher porosity (14%) and a higher permeability than the propylitically altered andesitic sample.

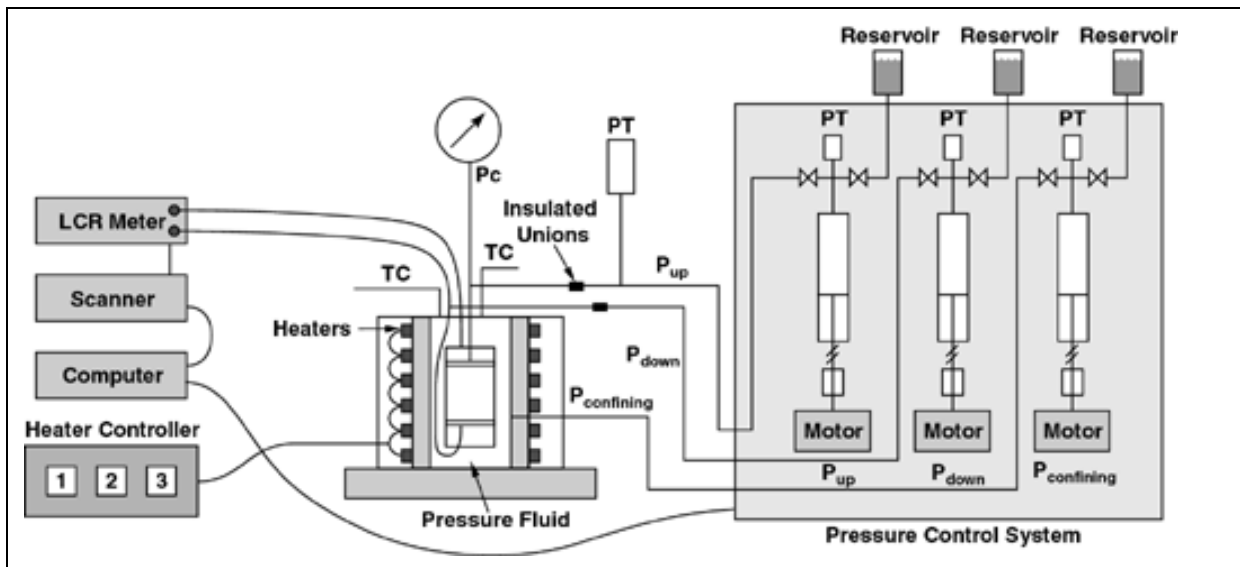


Figure 1. Schematic of apparatus. Sample is electrically isolated and held in an externally heated pressure vessel with separate reservoirs, pumps, and controls for confining and pore pressure. Type T thermocouples measure temperature of the three-zone heater and at two locations adjacent to the sample. An impedance bridge (LCR meter, HP4284a) is used to measure the electrical properties of the sample. A microcomputer controls the experiment and data collection.

Table 1. Samples Studied and Resistivity Ratios.

Sample	Description	Depth (ft)	Porosity	Resistivity Ratio [§] liquid	Resistivity Ratio [§] vapor (maximum)
4506	Awibengkok andesite	Run 76, 4506	3.0	0.4	3.7
3034	Awibengkok hydrothermal breccia	Run 27, 3034	14.0	0.8	2.3

§Ratio of resistivity of slotted to intact sample

Samples were prepared by machining right-circular cylinders approximately 2.0 cm high and 2.5 cm in diameter. Porosity was determined by subtracting dry density from wet density. Samples were saturated with a pore fluid prepared from high-purity salts and distilled water by taking samples dried under vacuum at 35°C and back-filling with the NaCl solution. Samples were then left immersed in the solution for several days until the weights were constant, indicating that saturation was complete. All samples were saturated with a mixture of 1.65 g NaCl per liter of water. The fluid was boiled for one hour before being used for saturating the samples to remove dissolved gases. The fluid used to saturate the samples was also pumped under rough vacuum for about 2 hours for more complete gas removal. Fluid resistivity at room temperature was $\sim 6.4 \text{ } \Omega\text{-m}$ (conductivity = 1.57 mS/cm). The sample assembly used in this study is shown in Figure 2. For some of the experiments at higher temperatures, KalRez (trademark DuPont) jacketing was used instead of Viton.

Cylindrical samples containing artificial fractures were prepared by cutting the samples in half lengthwise and regrinding the two halves to a cylindrical shape. The fractures were created by grinding a slot the entire length of one half of the sample. The dimensions of the slot are 0.5 x 20 x 19 mm for a volume of $\sim 0.19 \text{ cm}^3$ and the total volume of the sample is $\sim 10.2 \text{ cm}^3$. The slot was supported by ridges of rock left in place at the edges of the sample so that the slots remained open during experiments. The two halves were ground flat and when mated, only the slot permitted the free passage of fluid.

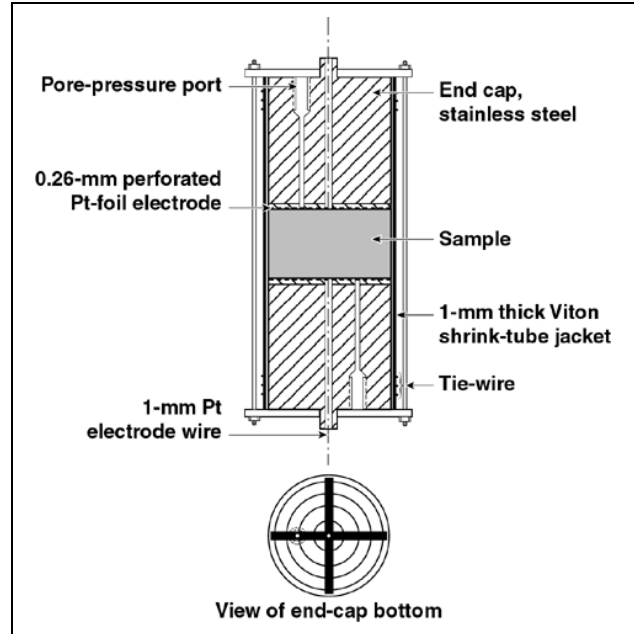


Figure 2. Schematic of sample assembly showing perforated endcaps, electrodes, jacket material, pore pressure inlets, and frame.

ELECTRICAL RESISTIVITY RESULTS AND DISCUSSION

Effects of Fractures on Resistivity

Resistivity as a function of pore pressure for samples 3034 and 4506 are shown in Figures 3 and 4. The confining pressure was held constant while the pore pressure varied. For the experiment on sample 3034, the confining pressure was 5.6 MPa for the intact sample and 3.5 MPa for the fractured sample. These starting pressures are such that the confining pressure:pore pressure ratios are approximately 2:1. For sample 4506 the confining pressure was 3.5 MPa for both samples. Previous studies show that the confining pressure has a minimal effect on the electrical properties of intact rocks of this type at these conditions (Llera et al., 1990; Duba et al., 1997).

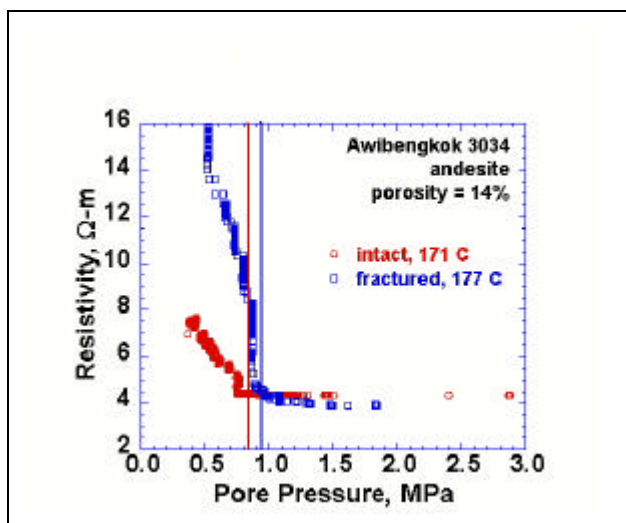


Figure 3. Resistivity vs pore pressure for Awibengkok sample 3034 at 171 (intact sample, circles) and 177°C (fractured sample, squares). Confining pressure was held constant while the pore pressure was changed. The vertical lines indicate the boiling pressure for water at 171 or 177°C.

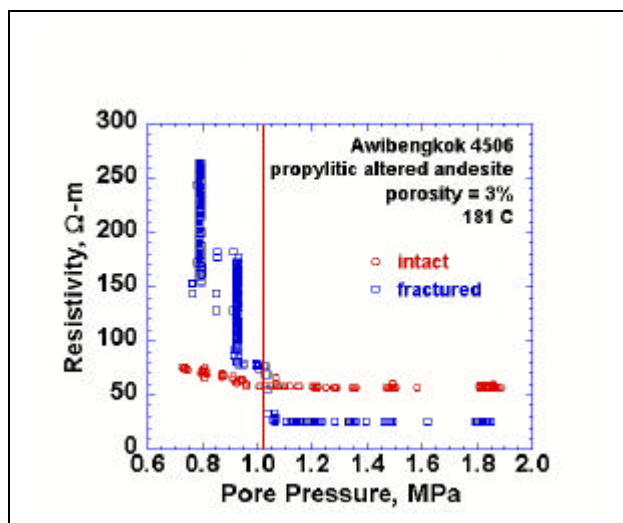


Figure 4. Resistivity vs pore pressure for Awibengkok sample 4506 at 181°C (fractured sample, squares; intact sample circles). Confining pressure was held constant while the pore pressure was changed. The vertical line indicates the boiling pressure for water at 181°C.

The data indicate several notable features. Considering the intact samples, the electrical properties are similar to previous results (Roberts et al., 2001) in that as the pore pressure is lowered little change in resistivity occurs until the boiling pressure is reached. At this point resistivity gradually increases as the pore is lowered further. The interpretation is that capillary forces in the smaller pores maintain the fluid in the liquid state. Both the samples studied here exhibit this behavior.

Both samples exhibit a resistivity ratio (of the fractured sample to the intact sample) that is less than one in the liquid region (to the right of the vertical lines on figures 3 and 4). This ratio is greater than one to the left of the vertical line (the boiling region; Haas, 1971) (Table 1). The addition of the fracture lowers the resistivity in both samples by providing a conductive pathway when filled with liquid water. This parallel conductor has a small effect on the most porous sample and a very large effect on the low porosity sample.

As the pore pressure is lowered below the boiling point of bulk water there is no immediate increase in the resistivity of the intact samples as a result of

vapor pressure lowering. The fractured samples show a resistivity increase immediately upon crossing the boiling pore pressure. At this pressure the resistivities of the intact and fractured samples cross, with the fractured samples suddenly significantly more resistive than the intact samples. A large resistivity change at the boiling pressure is expected because there is essentially no capillary suction in the relatively large sized slot. An unexpected result is the magnitude of the resistivity increase as pore pressure is lowered significantly past the boiling pressure. This effect is larger for sample 4506 (3% porosity) than for sample 3034 (14% porosity). Another interesting aspect of the two types of samples is the higher resistivity increases as pore pressure is lowered further. Our current interpretation is that more intact rock surface is exposed to the lower pressure so that more pores can easily lose water to the fracture. This creates a higher resistivity region adjacent to the fracture.

Mineral coatings on fracture surfaces will likely have an effect on the changing electrical properties of similar systems. Future work will attempt to address this by preparing samples that contain natural mineral coated fractures and performing similar experiments.

Fracture Detection Using Electrical Methods

Geophysical imaging methods that use electrical currents or induction to probe for fractures depend on detecting contrasts in resistivity associated with the fractures. Resistivity anomalies associated with fractures in the field depend on fracture density and aperture, resistivity of the fluid filling fractures and pores, and the electrical properties of the rock matrix. It is useful to discuss recent field scale measurements of resistivity (Ramirez and Daily, 2000) during heating and desaturation of a 3 x 3 x 5 m block of tuff at Fran Ridge, Nevada in the context of the new results obtained in this study. The field method was electrical resistance tomography, which assigns resistivity values to elements within the rock volume along current paths connecting transmitting and receiving electrodes. The host rock for the field test is a fractured tuff with porosity of ~11%, intermediate to the volcanic rocks tested in this study. The conductivity of the pore fluid at the beginning of the field test was 0.26 mS/cm, lower than that used for the experiments reported here. It is worth noting that conductivity of the pore fluid may have increased during measurements reported above when salt deposits in the pores dissolved as the samples were heated.

During the field test, the resistivity contrast (relative to the initial values) ranged from 0.2 to 1.2. Lowest values are correlated with increased water content in the partially saturated tuff. The highest values occurred in boiling regions, reaching the maximum of 1.2 after heating for two months. Independent measurements of water content by neutron logging confirm this general interpretation of tomographic results during desaturation of the block (Ramirez and Daily, 2000).

Resistivity measurements presented in Figures 3 and 4 are broadly consistent with the behavior observed in the field test. Lowest resistivity contrasts occur before boiling. Contrast increases after boiling in both laboratory and field tests, but reach larger values in the laboratory, as shown in Table 1. These initial results are encouraging and more detailed comparisons to the field measurements are underway. In particular, comparisons of electrical properties of fractured and intact samples of tuff from Fran Ridge will be made in the laboratory so that more detailed analysis of ERT results can be performed.

CONCLUSIONS

Resistivity of intact and fractured rocks is sensitive to temperature, composition and state of the pore fluid, and lithology. Measurements presented are a first step toward making the search for fractures using electrical methods quantitative. These measurements provide the first data for fractured geothermal rocks at reservoir conditions.

After steam is produced in the intact samples by lowering the pore pressure, the increase in resistance caused by replacing (in part) conducting brine with insulating water vapor is gradual and therefore inconsistent with an abrupt steam transition, as predicted by bulk thermodynamics. Resistivity data indicate that some pore fluid entrained within the matrix transforms to steam below the bulk fluid phase boundary. The observations are consistent with the "heterogeneous boiling" model, which occurs because vapor-pressure lowering and adsorption in fine pores maintains fluid in the liquid state across the phase boundary for bulk brine. The magnitude of the change of resistivity with boiling depends on porosity and surface conduction, and was much larger for the high-permeability hydrothermal breccia.

First experimental results for rocks with synthetic propped fractures reinforce the idea that electrical measurements provide a means for fracture detection. For the samples studied the saturated resistivity ratio is between 0.4 and 0.8 depending on porosity. During boiling conditions the resistivity ratio increases to between 2.3 and 3.7 at the lowest pore pressures of the experiment. The resistivity contrast increases with lower pore pressure and lower matrix porosity. Simple circuit element models suggest that resistivity contrast during boiling appears to be relatively insensitive to fracture aperture but increases with accessible fracture surface area.

The laboratory results are broadly consistent with field ERT measurements for fractured tuff, suggesting that fractures can be detected by locating the highest resistivity contrast regions. Monitoring the resistivity contrast before and after depressurization or fluid injection, for example, could provide important fracture indications. Localized high resistivities may be useful for locating and following permeable fractures and zones in the field when steam is present. The time dependence of the resistivity contrast may be useful for monitoring fluid migration from matrix rock into permeable fractures. Initial analysis of ERT data from a field scale experiment strongly suggest that interpretation of field resistivity using laboratory data will lead to improved understanding of fluid transport

in fractured reservoirs. Future efforts will focus on improving quantitative fracture detection by modeling additional laboratory tests and application of the results to the large scale field test on fractured tuff.

ACKNOWLEDGMENTS

W. Ralph, S. Fletcher, S. Carlson and C. Talaber provided essential technical support and expertise. We thank W. Daily for fruitful discussion and comments. This work was supported by the Office of Geothermal and Wind Technology, under the Assistant Secretary for Energy Efficiency and Renewable Energy of the U.S. Department of Energy, and was performed by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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